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Influence of ion nitriding on fatigue strength of low-alloy (42CrMo4) steel: Experimental characterization and predictive approach

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ABSTRACT

In this research the structure and fatigue properties of ion nitrided 42CrMo4 steel were evaluated and compared with a quenched and tempered structure. The fatigue limit were obtained by means of three-point bending fatigue tests for stress ratio ($R = 0.1$). The micro-hardness profiles were measured and used to demonstrate the case depth. The structure of surface layers and diffusion zone were examined by optical and scanning electron microscopy (SEM) and the in-depth residual stresses have been determined by the hole drilling technique. The improvement fatigue strength at 10^6 cycles was 35%. Explanation of the improvement was based on stabilized gradients of properties in treated layer occurred after cyclic relaxation. It results in a redistribution of hardness and compressive residual stresses that are favourable to the fatigue life. The high over-load sensitivity of the compound layer constitutes a serious limitation of the nitriding treatment in the low cycle fatigue domain. Based on multi-axial HCF criterion of Crossland and taking into account the different surface properties, which are: compressive residual stresses and superficial work-hardening, a local predictive approach was developed. Good agreement has been observed between the predicted results and those obtained from experimental investigations.

1. Introduction

The surface nitriding conditions have considerable influence on high cycle fatigue performance of mechanical parts; the principal effects induced in the near surface nitrided layers are classified and identified as follows: mechanical, metallurgical and surface integrity [1–5].

The mechanical modifications are characterized principally by compressive residual stresses distribution often favourable to high cycle fatigue resistance. They have little effect on crack nucleation, but can drastically delay crack propagation state. It is worth noticing that crack nucleation sites were observed, some times, below nitrided surfaces, where tensile residual stresses are present to balance the outer compressive stresses field. The metallurgical modifications observed in the majority of nitrided steels are favourable surface work-hardening (it delay crack nucleation) [6,11–13].

The techno-economical interest of nitriding justifies the many studies devoted to the control of the process parameters which control the structure and the properties of the nitrided layers. Cracking fatigue resistance of nitriding component depends on the surface features. Witch is the structure of treated layers, its depth, the hardening level and the state of residual stresses. However, the nitriding effect can be reduced or even reversed when the compound layer is submitted to dynamic or static stresses, especially in plastic domain [2,4,5,9–11].

The prediction of the fatigue strength improvement of the nitrided layers is difficulty controlled because of the properties evolution of the treated layers with the cyclic loading. Deperrois proposed a model for the prediction of high cycle fatigue of superficially treated parts [15]. It takes into account the two favourable effects of the compressive residual stresses and the surface work-hardening.

One has in this work the results relating to the role of the quality of the compound and diffusion layers in the bending fatigue resistance of the 42CrMo4 steel. The nitriding contribution is quantified in term of the endurance limit at 10^6 cycles in bending fatigue. It is discussed in relation to the nitrided layers microstructure, the residual stresses distribution under cyclic loading and their influence on cracks nucleation and propagation of the fatigue strength. And we developed an approach to predict high cycle fatigue behaviour of nitrided parts, taking into account favourable and unfavourable effects of the nitrided surface properties.

2. Material and experimental tests

2.1. Studied material

The studied material is a 42CrMo4 steel, usually used in mechanical industry for the manufacturing of the transmission

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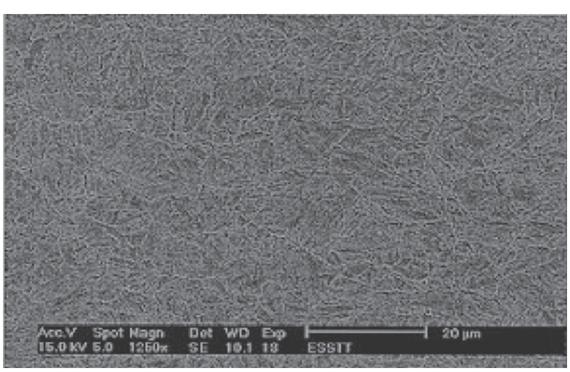
Nomenclature

$\underline{\underline{\sigma}}(t)$	cyclic stress tensor at an instant t having T period
$\underline{\underline{S}}(t_i) - \underline{\underline{S}}(t_j)$	cyclic stress deviator tensor at two different instants t_i and t_j respectively
$tr\underline{\underline{\sigma}}(t)$	trace of the cyclic stress tensor at an instant t
σ_{Eq}	equivalent stress appearing in the Crossland criterion
Δ_{coct}, a	octahedral shear stress amplitude
$P_{\max}$	maximum hydrostatic pressure
$\sigma_{\max}$	the fatigue limit (the maximum applied stress)
$\Delta\sigma_1$, $\Delta\sigma_2$	fatigue limit range at 10^6 cycles obtained under three-point bending fatigue tests with two stress ratios $R_1 = 0.1$ and $R_2 = 0.5$ respectively
α_C and β_c	material parameters appearing in the Crossland criterion
β_0	untreated material parameters appearing in the Crossland criterion
I (%)	high cycle fatigue indicator
n	material constant appearing in the β_c expression
σ_{Rxx}, σ_{Ryy}	relaxed residual stresses in X and Y directions respectively
$\underline{\underline{\sigma}}_R$	the relaxed residual stress tensor
$\underline{\underline{\sigma}}_{app}$	applied cyclic loading tensor at an instant t
$\underline{\underline{\sigma}}_t$	total cyclic loading tensor at an instant t

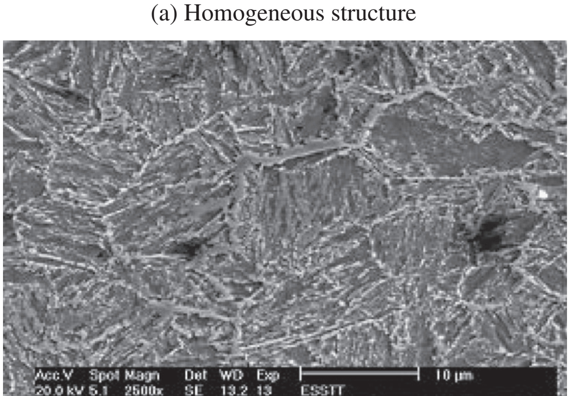
Table 1
Chemical composition of studied steel.

C	Mn	Si	S	Cr	P	Mo	Ni	Al	Cu	V	Ti	Fe
0.41	0.77	0.28	0.026	1.02	0.019	0.16	0.16	0.04	0.25	<0.01	0.03	Bal.

parts (gears, shaft, etc.) or of the moulds of plastic injection. Its contents of alloy elements are presented in Table 1. Its structure, in a reception state (untreated), resultant from the oil quenching after austenisation, at 850 °C and tempering at 580 °C during 1 h, consists of tempered martensite (Fig. 1a), with a carbide precipitation which decorate the old ferrite boundary, (Fig. 1b). The core hardness of this tempered martensite structure is close to 356 HV_{10kg}.



(a) Homogeneous structure



(b) Carbides with the grain boundaries

Fig. 1. Tempered martensite structure of the untreated state.

2.2. Treatment

The ionic nitriding of the studied steels aims to obtain a depth of hardening about 300 µm. The parameters of this treatment are reported in Table 2.

2.3. Experimental investigations

The layers nature identification was carried out by X-rays diffraction analyses and metallographic tests under the optical microscopy (OM) and scanning electronic microscopy (SEM). The control of nitriding hardening was carried out by micro-hardness tests ($HV_{0.05}$) on transverse sections using a Shimadzu micro-hardness tester HMV-2000.

The residual stresses state in the nitrided layer was given at the ambient temperature by X-rays diffraction on the surface under the conditions listed in Table 3. The residual stress profiles in-depth were established using the hole drilling method. The holes were drilled incrementally by a 2 mm diameter drill rotating at a high speed (2500 rpm) to avoid inducing additional residual stresses.

Table 2
Nitriding Conditions.

Steel	Nitriding	Temperature (°C)	Duration (H)	N_2 (%)	H_2 (%)
42CrMo4	Ion-nitriding	520	20	20	80

Table 3
X-ray diffraction conditions.

Target	Cr
Wavelength (A°)	2.2897
Filter	V
Current (mA)	5
Voltage (kV)	20
Goniometer tilt	ψ
Young's modulus, E (GPa)	210
Poisson's ratio, ν	0.33
Number of ψ angles	13 (from −36.3° to +39.2°)
Number of θ angles	2 (0° and 90°)